EFFECT OF CURVATURE AND DIFFUSION ON FLOW THROUGH RECTANGULAR DUCTS

by

M. SRINIVASA RAO

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DEPARTMENT OF AERONAUTICAL ENGINEERING

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M. SRINIVASA RAO

to the

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CERTIFICATE

3/4/89

This is to certify that the thesis entitled

Effect of curvature and diffusion on flow through rectangular ducts.

is a record of the work carried out under my supervision and that it has not been submitted elsewhere for awarding a degree.

(R.K.SULLEREY)

PROFESSOR

Dept. of aeronautical engineering.

Indian institute of technology

Kanpur

Dated : 3.4.89

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M.SRINIVASA RAO

CONTENTS

NOMENCLATURE

AR	*AREA ratio expressed as a ratio of exit area to the inlet area.*
AS	*ASPECT ratio expressed as the ratio of width of the duct to the inlet height*
Cp	*Static pressure coefficient*
d	*height of the duct*
d_1	*height of the duct at the inlet*
d_2	*height of the duct at the exit*
h	*In graphs it is the width of the ducts in which experiments were carried out.*
L	*length of the ducts measured along the centre line*
L_{in}	*inner wall length.*
L_{out}	*outer wall length.*
P_i	*static pressure at the i^{th} station.*
P_α	*static pressure at the reference point.*
R	*radius of curvature.*

$2r$	width of the ducts ,kept constant throughout the experiments.
U	mean velocity of the flow.
U_{max}	maximum velocity of the flow.
U_{∞}	velocity of the flow at reference point.
y	distance measured perpendicular to the walls.
ρ	density of air at 25^{o}c.
θ	semi-angle of divergence.
ϕ	turning angle.
δ	boundary layer thickness.

LIST OF PHOTOGRAPHS.

LIST OF FIGURES

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THESIS SUPERVISOR : Dr. R.K.SULLEREY

: Professor

Dept. of aeronautical engineering.

I I T KANPUR

ABSTRACT

Two dimensional intakes are used in many combat aircrafts as they are considerbly less sensitive to oblique flows. The function of the inlet duct is to supply the compressor with the required amount of air at an acceptable flow Mach number with the highest possible pressure recovery and minimum flow distorsion.The subsonic portion of the intake has complex geometry with curvature coupled with area increase(i.e.divergence.).The present study is motivated to study the flow behaviour in two-dimensional ducts with curvature and divergence angle range typical of two-dimensional air intakes.

The present experimental investigations have been carried out on a curved duct without diffusion and a curved diffser with a divergence angle of 6^{0}.Both the ducts have the ratio of radius of curvature to half the duct width as 6 and length of ducts to the width of the ducts as 5 with a turning angle of 95.5^{0}. All the measurements were carried out at Reynolds number of 7.8×10^{5} based on the duct width.

The results presented include the pressure distribution along inner,outer and bottom walls and average pressure recovery along the length of the ducts.Boundary layer measurements have been carried out on the inner and outer walls for both the ducts. Velocity profiles at various stations have been presented with in and outside the boundary layer. Boundary layer thickness has been calculated and the extent of separated region was obtained in case of separated flows.The extent of separated region was found to be 40% of half the duct width at the fifth station on the inner wall. No flow separation was observed in case of outer wall.

Measurements have also been carried out for the two ducts at a higher value of free stream turbulence of 4.37%. The results indicate that performance of the curved diffuser improved at higher value of free stream turbulence level.However,the flow behaviour in the curved duct without diffusion was unaffected at higher free stream turbulence levels. It is expected that the data obtained in the present investigations would be useful in the design of subsonic curved ducts of aircraft intakes.

C H A P T E R -1

INTRODUCTION

All current aircraft engines require subsonic flow for entry into the compressor. In supersonic flight the flow must therefore be reduced to the specified entry mach number for the engine, which lies between 0.4 and 0.7 respectively. Conversly, the flow in the inlet duct has to be accelerated when the flow speed is too low, as for example when static and during low speed flight. These requirements are met by the intake. The function of an intake is to deliver required mass flow at the compressor face with the highest possible stagnation pressure,and with smoothest possible velocity distribution.Any loss in stagnation pressure represents a performance loss for the engine while variations in velocityaround an intake are liable to cause compressor surging or blade vibrations.These requirements are to be met not only during normal flight,but also at different speeds,altitudes and also on the ground when aircraft takes off and requires maximum thrust.

The air requirement of the engine determines the flow speed at the compressor face.At low speeds the flow accelerates inside the duct.And at high speeds the dynamic pressure has to

be converted in to pressure rise. Thus the conversion of the kinetic flow energy to pressure is continued in an inlet duct by increasing the cross sectional area in the direction of flow gradually and steadily. A divergent air duct with the capacity to decelerate a subsonic flow in this way and, at the same time to build up pressure is called a diffuser. But often due to space limitation, the flow in addition to deceleration has to be turned also, in a curved diffuser.

Though the axi-symmetric fixed or variable geometry conical intakes are more generally used in supersonic aircrafts due to the advantages of less pressure loss, they are equally unfavourble when the flow is not symmetric to the axis of the cone but is at an angle to it. This state occurs during side slip and turning flight manoevures and leads to severe distortion causing the compressor to operate in the dangerous surge limit area. In contrast, the two-dimensional intake is considerably less sensitive to oblique flow, even if the pressure recovery which can be attained is less favourable. Numerous modern combat aircraft designs are equipped with inlets which are two-dimensional air intakes, such as F-14, F-15, MIG-25. This inlet shape is also found in CONCORDE and TU-144 civil supersonic aircraft.

Some other applications of the flow over curved surfaces are blade passages of the turbomachinery,vaned diffusers of centrifugal compressor stages,in steam turbine exaust hoods and in interconnecting ducting between components in gas turbine.

The present experimental study consists of not only about curved diffusers but also a curved duct without any diffusion due its numerous applications like blade passages of turbomachines etc.

The literature survey for the present experimental study has been presented in two parts ,one for the curved diffuser and the other for curved duct.

1.1 Literature survey for the curved diffuser :

The performance of a diffuser is generally evaluated in terms of pressure recovery. The main problem associated with the diffusing bend is flow seperation which results in non-uniform flow distribution and excessive losses.

Moore& Kline(1) have shown that flow regimes of simple diffuser depends on the total divergence angle,wall length to throat width ratio and the free stream turbulence. The variations in throat width reynolds number and the throat

aspect ratios normally encounterd had little or no effect on the flow regimes.

Fox & Kline(2) have systematically investigated the flow regimes of curved diffusers.They concluded that flow regimes can be discribed in terms of inlet length to width ratio,area ratio and the turning angle.They have also concluded that there was a rapid drop off in allowable area ratio for the first stall limit as the turning angle increased.The turning angle variations in their investigation was from 0 to 90 degrees.

Sagi & Jhonston(3) have explained the drop off in performance and area ratio interms of less favourable innerwall boundary layer growth.The innerwall is subjected to the following curvature induced effects.(i) Increased potential flow loadings along the wall.(ii)Reduced turbulent mixing along the wall.(iii) Increased thickness of the innerwall boundary layer caused by secondery flows off end walls.

Ichiro (4) et.el have tested circular arc centre line diffusers with different effective divergence angles and have presented the distribution of pressure coefficients on inner and outer walls versus angular positions. Assuming approximate displacement thickness,a theoretical distibution of pressure coefficient was calculated which agreed with the measuments.

Sullerey et al (5) have conducted an experimental investigation for the comparison of straight and curved diffusers having the same area ratio and found that with an increased free stream turbulence the performance of a curved diffuser was improved more than that of a straight diffuser with the same amount of free stream turbulence.

Kunik (6) has presented a model for the analysis of vortex generators in fully viscous subsonic internal flow.The computed results are compared with the experimental data for vortex generators embedded in a thick turbulent boundary layers.He concluded that the model can be used to indicate where to place the vortex generators and what angles they should be set at to reduce the seperation.

1.2 Literature survey for curved duct without diffusion :

The effect of curvature on turbulent boundary layer was first investigated by Wilcken on both convex and concave walls.He concluded that the centifugal force (due to the curvature) at the concave wall promote turbulent mixing between adjacent fluid layers,while the opposite takes place at the convex wall (i.e reduced turbulent mixing) there by increasing the eddy viscosity and mixing length near the concave wall than that near the convex wall.

Wattendorf (7) has conducted experiments in two circular arc curved channels of constant curvature and ratio of half

cannel width to mean radius of curvature as 1/19 and 1/9 and found that deviation of law of wall is in opposite directions for convex and concave walls.

Eskinaji & Yeh (8) have conducted experimental investigations on a curved channel of ratio of innerwall radius to outer wall radius of 0.9 and turning angle of 150 degrees. Besides mean flow measurements, they also conducted turbulence measurements and found that turbulent intensities were greater near the concave wall than that near convex wall.

So & Mellor(9) have investigated the turbulent boundary layer flows with both uniform and adverse pressure distributions along convex and concave walls having 150 degrees turning angle. Hot wire measurements along the convex surface indicated that the turbulent mixing between fluid layers was reduced significantly and a system of longitudinal vortices were observed inside the boundary layer of a concave wall.They concluded that the intensity of the turbulence along convex wall is reduced due to the favourable pressure gradient existing along the convex wall,while the converse takes place at the concave wall.This indicated that the ability of the flow to support adverse pressure gradient along convex curvature is reduced compared to that of a plane wall flow. The opposite effect takes place along the concave wall making it to support more adverse pressre gradient than a parallel flow without separation.

Ramprian & Shivaprasad (11) have conducted an experimental investigation on a curved channel of the ratio of boundary layer thickness to the radius of the wall of 0.013 and found that where as the region close to the wall was not affected significantly by the wall curvature ,the outer region was very sensitive to even mild wall curvature.

1.3 Scope of the present investigations :

Basically, the task of every inlet is to supply the engine with a uniform ,stable and low loss flow.The operational spectrum of intakes for which satisfactory performance must be produced includes take off and landing ,low speed flight ,high speed flight(subsonic),manoeuvreing flight and the high speed flight(supersonic).The different flow behaviour at subsonic speed and supersonic speed also effects the properties of the inlet so that the inlet configuration is largely dependent on the mach number range for which the aircraft is designed.

The present experimental investigations were conducted on a two-dimensional curved diffuser and a curved duct both having a turning angle of 95.5 degrees,at a Reynolds number of 7.8×10^5 and at inlet Mach number of 0.1.Though the design for the curved diffuser has been carried out for four semi diffusion angles from 3 to 6 degrees,only 6 degree semi angle case was investigated due to the time

limitations.The present curved channels used have a ratio of radius of curvature based on half cannel width as 6 and a length of duct based on channel width as 5.

Performance curves like pressure coefficient, velocity profiles and boundary layer profiles were plotted at different radial stations as mentioned in the experimental setup. Static pressure coefficient variations on inner(convex),outer(concave) and bottom walls were plotted at different radial stations along the length of the ducts with and without turbulence grid, to investigate the effect of free stream turbulence.velocity profiles were also plotted at different radial stations both in vertical and horizontal axes in case of curved duct and in horizontal axis in case of curved diffuser.

All the experiments were conducted with a flow having uniform velocity profile at the inlet to both curved diffuser and curved duct.

Though the present designs of curved diffusers are not directly used as an intake in aircrafts, it is expected that results of these investigations would be useful in the design of subsonic curved ducts of aircraft intakes. The mesured data for these simple configurations could also be used for validating computer codes usually used during intake design process.

CHAPTER 2.

EXPERIMENTAL PROGRAMME

2.1 DESCRIPTION OF WIND TUNNEL :

The tunnel which is used in the present investigations is an open circuit blower type low speed wind tunnel,with an exit cross section of 38.1 X 30.48 and a contraction ratio of about 10.The blower is driven by a 30hp constan speed motor(1400 rpm) and shutter arrangement near the eye of the fan provides for the control of air speed ranging from a minimum of 25m/s to a maximum of 54 m/s at 25 °c and at atmospheric pressure. the reynolds number range corresponding to these speeds are 7.8×10^5 to 1.29×10^6 based on channel width. The maximum air flow rate is 270 cu m /s.

2.2 DESIGN OF CURVED DIFFUSERS AND CURVED DUCT :

In the design of aircraft intakes the following parameters are usually used as design parameters.

(i) radius of curvature.

(ii) length of diffuser as measured along the centre line.

(iii) divergence angle.

The typical range these parameters relevant to aircraft intakes are R/r ratio from 4 to 8, L/2r ratio from 3 to 7

and the semi divergence angle variation from 3 to 6 degrees. The present design of the ducts have been carried by taking R/r ratio as 6 and L/2r as 5 with semi-diffusion angle variation from 3 to 6 degrees.

Photographs 1,2,3 & 4 shows curved duct and curved diffusers with and without their assembling to the tunnel nozzle exit.

The main feature of the present designs is that a single diffuser set up has been used for varying the divergence angle from 3 to 6 degrees by varying top and bottom walls. the turning angle obtained from the above ratios of R/r equal to 6 and L/2r equal to 5 is 95.5 degrees.The design parameters of the curved duct and curved diffusers have been shown in the tables 1 and 2 respectively.The inlet width of the ducts have been kept constant at 38.1cm.

TABLE 1

S.NO	2r cm	d_1 cm	d_2 cm	R cm	L cm	L_{in} cm	L_{out} cm	θ	ϕ	AR
1	38.1	30.48	50.44	114.3	190.5	158.76	222.26	3^0	95.5^0	1.65
2	38.1	30.48	57.12	114.3	190.5	158.76	222.26	4^0	95.5^0	1.9
3	38.1	30.48	63.81	114.3	190.5	158.76	222.26	5^0	95.5^0	2.1
4	38.1	30.48	70.52	114.3	190.5	158.76	222.26	6^0	95.5^0	2.31

TABLE 2

S.NO	2r	d_1	d_2	R	L	L_{in}	L_{out}	θ	ϕ	AS	AR
1	38.1	30.48	30.48	114.3	190.5	158.76	222.26	0^0	95.5^0	1.25	1

The inner and outer walls of both the ducts were made of 5mm thick perspex sheet for smooth working surface. The top and bottom walls of both the ducts were made of 12mm thick plywood.

The diffusers and the duct had a frame at the inlet so that it can be tightened to a straight par allel duct placed at the exit of the tunnel nozzle by C-clamps. Two more frames were also made for both the ducts for handling purposes,one at the middle and the other at the exit of the ducts. In addition to a straight parallel duct at the inlet to the curved it is also provided with another parallel duct placed at its exit to prevent any ambient air currents from effecting the flow in the duct.

2.3 MEASUREMENT TECHNIQUE AND INSTRUMENTATION :

Wall static pressure :A row of wall static pressure tappings of dia1.5mm were provided at 5 degree intervals from the start of the curved portion on the centre line of both the ducts at inner,outer and bottom walls.The bottom walls of both the ducts were also provided with two more rows of pressure tappings ,7.5cm on either side of the centre line. In addition to the centre line tappings,two more rows of static pressure tappings were also provided on inner and outer walls ,7.5cm on either side of the centre line to check the pressure variation in the transverse direction.The locations these pressure tappings for both the curved duct and curved diffuser were shown in the fig 1 and fig 2 respectively.

velocity measurements : In the present experimental investigations,the velocity profiles were obtained with the help of the pitot tubes as shown in the fig 3.The relevance of the present technique for measuring velocities in curved ducts has been given in the references (10) and (11).

For obtaing velocity profiles ,slots of 12mm dia were made on the top wall of both the ducts.The measuring stations are given in the tables 3 and 4 for curved duct and curved diffuser respectively

.TABLE3

STATION	1	2	3	4	5	6
ϕ	15^0	30^0	45^0	60^0	75^0	90^0

TABLE4

STATION	1	2	3	4	5	6	7	8
ϕ	10^0	20^0	30^0	40^0	50^0	60^0	70^0	80^0

Due to the presence of joints in the inner and outer wall regions, the slots are not made up to the full radial distance but are 38mm away from both the inner and outer walls.Therefore for taking near wall measurements, small holes of dia 6mm was provided at the centre of inner and outer walls matching with the top wall slots. The wall measuements were taken by inserting the pitot-tubes through the holes and aligning them in the radial direction.

For obtaing velocity profiles,three types of probes were used in the present investigations.One is a pitot -disc probe combination and the other two are simple pitot tubes. They are shown in the fig 3.

A dweyer gauge manometer was used for the pressure measurements.The range of this manometer is 0 to 3 inches. This manometer had a high accuracy in the lower speed range.

A DISA constant temperature hot wire anemometer was used in the measurements of free stream turbulence level.The wire of the probe is made of platinum with silver coating and had a dia of 0.015mm and a length of about 1mm.

A THREE-DIMENSIONAL traversing mechanism was used for traversing the pitot tubes during the velocity measurements in both the ducts.The accuracy of the movement in the vertical direction is 0.05mm while that in the horizontal direction is 0.6mm.

A grid was placed at the exit of the tunnel nozzle for increasing the free stream turbulence level. The turbulence level of the free stream wasincreased from 0.6% to 4.37% with the grid.The diameter of the wires used to form the mesh is 12mm.

2.4 *TESTING TECHNIQUE :*

The present experimental investigations consists of static pressure measurements along inner,outer and bottom walls of both the ducts.velocity profiles were drawn at different stations in the radial direction.Pressure measurements with a turbulence

generating grid was also carried out.All the measurements were carried at a flow velocity of 25m/s at the nozzle exit.

2.4.1 velocity profile at the inlet :

The velocity profile at the inlet to both the ducts were taken in the vertical direction from top to bottom with the help of a pitot-static probe of dia fixed rigidly to a traversing mechanism .The two tubes from the pitot-static are connected to a dweyer gauge manometer.More number of points were taken near the walls than that at the central region of the ducts as the profile was expeæted to deviate due to the presence of boundary layer. The velocities at different points were calculated by using the formula $U = 12.65\sqrt{h}$ where h is head in cms of water.The profile obtained from the above set of data is shown in the fig 4.

2.4.2 pressure measurements :

Static pressure measurements were taken on the inner,outer and bottom walls of both the ducts. The locations of the pressure tappings were shown in the fig 2 and fig 3 for curved duct and curved diffuser respectively. For all the measurements, a pressure tapping located at the centre of the straight parallel duct was taken as the reference point. The static pressure coefficient was calculated from the formula $Cp = \dfrac{P_i - P_\alpha}{1/2\,\rho\, u_\alpha^2}$

The static pressure measurements were also taken after placing a turbulence grid(for increasing free stream turbulence)at the exit of the tunnel nozzle.

2.4.3 velocity measurements in a curved duct :

The velocity profiles in case of a curved duct were taken at different stations (as shown in the table 4)in the vertical as well as in the horizontal axis. All the mesurements were taken in the radial direction at the centre of the duct.

The measurements near the walls were taken with the help of pitot-probes as shown in the fig 3b and fig 3c.The assumption in carrying out the near wall measurements with the help of pitot probes is that the static pressure is constant in the boundary layer.In the free stream ,the measurements were taken with the help of a pitot- disc probe shown in the fig3a.The error in aligning the three probes along the same radial direction is below 2%. The velocity profiles were shown in figures 7 to 11.

2.4.4 velocity measurements in curved diffuser :

The velocity profiles in case of curved diffuser were taken at different stations shown in the table 3. All the velocity profiles were drawn at the centre of the duct in the radial direction .The measured velocity profiles were shown in figures 14 to 16.

C H A P T E R 3

Results and discussion.

The present experimental investigations consists of three parts firstly experiments have been carried out in a curved rectangular duct of R/r ratio of 6 and L/2r ratio of 5.In the second part of the study the effect of divergence has been investigated togetherwith curvature for a curved diffuser of semi divergence angle of 6 degrees.Although diffuser design allows variation of semi divergence angle from 3 to 6 degrees,the effect of divergence angle was not investigated for other anglesdue to the time considerations.Third part of the study is concerned with effect of free stream turbulence on flow behaviour in both the ducts.The presentation of the results has been made in the above order.

3.1 *Curved rectangular duct without diffusion.*

Fig 5 shows the variation of static pressure coefficient on the inner and outer walls.Also shown in the figure is the wall static pressure ditribution at the centre of the duct as obtained from the bottom wall pressure taps. The pressure increases from inner wall to outer wall due to the the effect of the curvature .The drop in average pressure along the duct is also shown in the

figure.The centre line pressure is higher than the average pressure although the difference is not significant.

Fig 6 shows pressure distribution with a short parallel duct placed at the exit of the curved duct.Except a smooth variation of pressure distribution from the inlet of the duct to the exit of duct ,there was not much change obsereved from the previous case.

The pressure distribution on the inner and outer walls was measured using three different pressure taps at all the measuring stations(as mentioned earlier). There was not much change observed in the readings of the different pressure taps .The results presented in fig5 and 6 correspond to the pressure taps at the center.

Figures 7 to 10 present the velocity profiles across the duct along the radial direction at different angular stations.The traverses have been taken at 10 degree intervals.

Fig 7 shows the velocity profiles at the first and second stations . The potential flow velocity profile shows a peak near towards the inner wall and the free stream velocity decreases towards the outer wall.The distribution of measured potential flow velocity follows the same trend as obtained from theory. However due to the losses the measured velocities are slightly higher than the theoritical values.On the inner and outer walls ,there is agrowth of boundary layer.The inner wallboundary layer is substantially thicker than the outer wall as shown in the fig 11.

Figures 8 to 10 show velocity profiles from stations 3 to 8.The flow behaviour is similar in the sense that there is an acceleration of flow near the inner wall and deceleration near the outer wall.The angular momentum(i.e UR) values as calculated from the measured velocities were found to be constant although somwhat higher than the theoretical values by about 4%.This confirmed that the flow was behaving like a free vortex flow except for the effect of boundary layer.

No flow separation was observed in any of the eight stations where measurements have been taken.Boundary layer thickness calculated from the above velocity profiles show that it is increasing from the inlet of the duct to the exit.The boundary layer thickness variation along the eight stations was shown in the fig 11.It was also observed that the peak velocity increased along the length of the duct by about 10% from the initial peak value.

. Fig 12 show velocity profiles in the vertical direction at the first radial station .It was plottedat three diffeent positions . one at the centre of the duct and the other two at ,7.5cm on either side of the centre of the duct. Flow is uniform from top to bottom walls confirming that the flow is two- dimensional. Boundary layer growth in the top and bottom walls was found to be less significant.It was also observed that the flow in the verical direction was not effected by curvature at any of the eight

stations where measurements have been taken.

3.2 CURVED DIFFUSER WITH A SEMI-DIVEGENCE ANGLE OF 6^O.

FIG 13 show variation of static pressure coefficient on the inner and outer walls. Also shown in the figure is the wall static pressure distribution at the centre of the duct as obtained from the bottom wall pressure taps.Pressure recovery obtained on the inner wall is less than that on the outer wall. Initially there was pressure drop on the inner wall until 17.5^O.This could be attributed to the greater infuence of curvature than divergence on the innerwallnear the inlet of the duct.The pressure increase on the inner wall started only after $17.5^O$of turning angle due to the effect of divergence (i.e area increase). In the case of the outer wall, divergence had the dominant influence as compared to the curvature starting from the inlet to the exit of the duct.This fact can be seen from the Cp values obtained at the initial stations.the Cp values at the inner and outer walls are -0.115and 0.23 respectively at the first station.

Fig 14 show the velocity profiles at the first and second stations (each station is at 15^O interval) in the radial direction.All the velocity profiles have been taken at the centre of the duct. The velocity profiles have a peak near the inner wall as in the case of a curved duct without divergence.Also the mean velocity is decreasing towards the outer wall.It was also observed that the peak of velocity has shifted towards the

centre of the duct by about 33% from that at the first station.

Fig 15 shows the velocity profile at the third station.It was infered from the figure that boundary layer was separated near the inner wall. The extent of the separated region was found to be 24% of half the duct width from the inner wall.The peak of the velocity profile has now shifted to the centre of the duct.

Fig 16 show the velocity profiles at the fourth and fifth stations .The separated region has further extended up to 40% of half the duct width from the inner wall.The peak of the velocity further shifted by about 27% from the centre of the duct. The magnitude of the peak velocity drop between inlet and exit of the duct was found to be 60%.

3.3 *COMPARISON OF THE DUCTS* :

Both divergence and curvature effects have dominant influence on the flow particularly on the inner wall in the sense that the flow behaviour was drastically deviated from the free stream flow.The pressure recovery in the diverging duct takes place only after 17.5^{0} of turning angle .Flow separation was also observed on the inner wall between 30^{0} and 40^{0} and extended up to the exit of the duct.This confirms that ability of the flow to support adverse pressure gradient without separation on the inner wall is very much reduced as compared to a parallel flow.On the other hand flow can support a higher adverse pressure on the outer wall as compared to a parallel flow.

3.4 *EFFECT OF FREE STREAM TURBULENCE :*

The effect of free stream turbulence on the flow behaviour was investigated by increasing the free stream turbulence level from 0.6% to 4.37% (both at the same reference point as mentioned earlier.) by a grid placed at the exit of the tunnel nozzle .

Fig 17 shows variation of static pressure coefficient on the inner and outer walls of the curved duct. There was no obsevable change in these distributions when compared with the original measuements at low turbulence levels.

Fig 18 show the average static pressure distributions with and without turbulence generating grid along the length of the duct. More pressure drop was observed onward from 50 ^{O} turning angle ,when the free stream turbulence level was increased to 4.37% from the initial level of 0.6% .

Fig 19 show the variation of static pressure coefficient on the inner and outer walls of a curved duct with a semi - divergence angle of 6 ^{O}. Increased free stream turbulence level has shown more improvements on the pressure recoveries of inner and outer walls.How ever the increased free streamturbulence level has more significant effect on the pressure recovery of innerwall than that on the outer wall. The pressure recoveries of inner and outer walls are 25% and 16% more than the corresponding

recoveries at the initial turbulence level of 0.6%, respectively.This is likely due to a positive effect of free stream turbulence in suppressing the separation of the inner wall boundary layer.

Fig 20 show the average static pressure distributions with and without grid along the length of the curved diffuser.It was observed that the average pressure recovery obtained with increased free stream turbulence level is 23% more than that with the initial free stream turbulence level.The effect of increased free stream turbulence level on the pressure recoveries started from the first station itself.This is a significant improvement in pressure recovery.

CHAPTER 4

CONCLUSIONS

The following conclusions can be drawn from the present experimental investigations, carried out on a curved duct and a curved diffuser of semi divergence angle 6 ^{0}.

Flow behaviour on the inner and outer walls of a curved duct are opposite in nature. The pressure is dropping along the inner wall until 75^{0} of turning angle and then increasing up to the exit.While the same along the outer wall is increasing up to 40 ^{0} and there after decreasing until the exit.Boundary layer growth on the inner wall is observed to be more than that on the outer wall.No separation of boundary layer was observed in the curved duct for the turning angle upto95.5 ^{0} used in the present experiments.

The increased free stream turbulence level has negligible effect on the behaviour of the flow through the curved duct.No pressure distribution change was observed by placing a short parallel duct at the exit of the curved duct.

The effect of divergence had more positive influence on the flow behaviournear the outer wall. In this case pressure started from the first station itself.However there is no pressure rise on

the inner wall until 17.5^{0} of the turning angle.

Ability of the flow to support adverse pressure gradient is reduced incase of the inner wall while it improved along the outer wall. separation of the boundary layer on the inner wall occured between 30^{0} and 45^{0} of the turning angle and continued until the exit The extent of the separated region increased from 24% of half the duct width at third station to 40% of the half the duct width at fifth station.

Increasing the free stream turbulence level to a higher value can drastically increase the pressure recoveries obtained on the inner and outer walls.Improved pressure recoveries obtained with increased free stream turbulence level of 4.37% from 0.6% on the inner and outer walls are 25% and 16% respectively. The average pressure recovery was increased by 23% .

Due to the lack of time the effect of other angles on the flow behaviour was not investigated, even though diffuser design has allowed such variation.However it is expected that the lower diffusion angles will give uniform exit velocity profiles at a turning angle of 95.5^{0} with good presssure recoveries.

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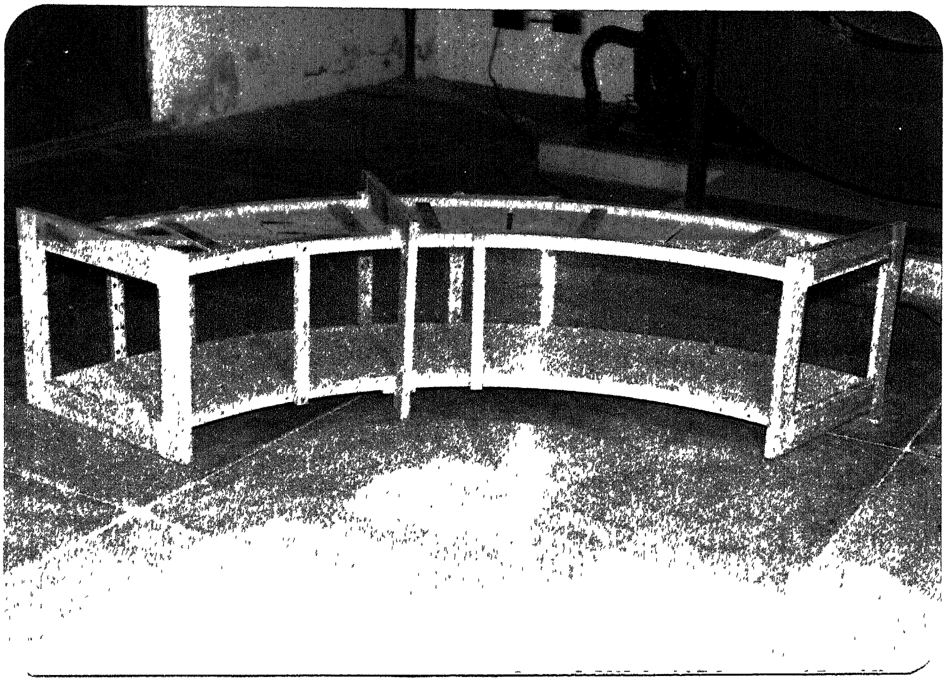
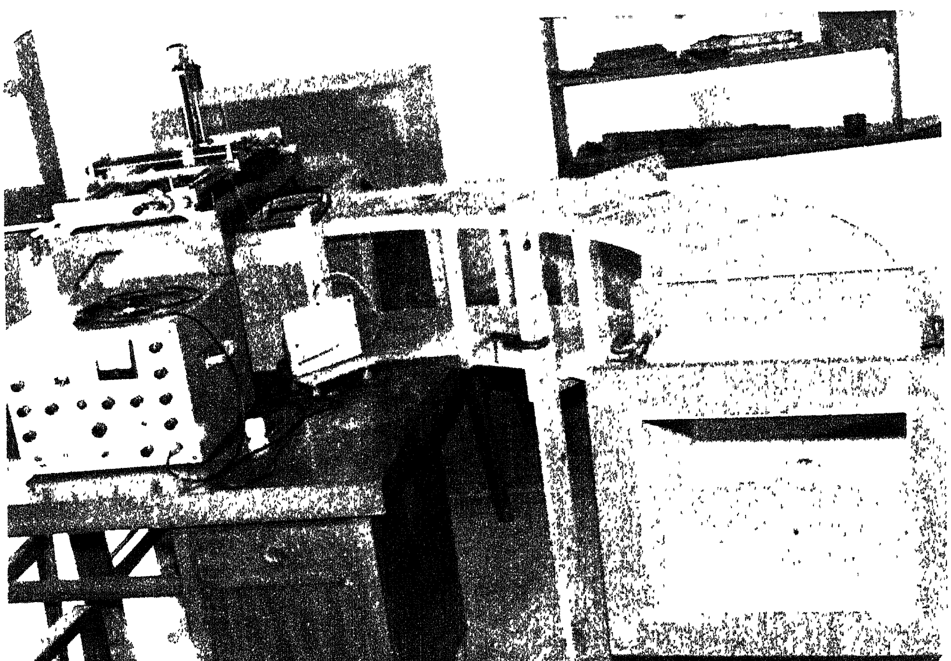
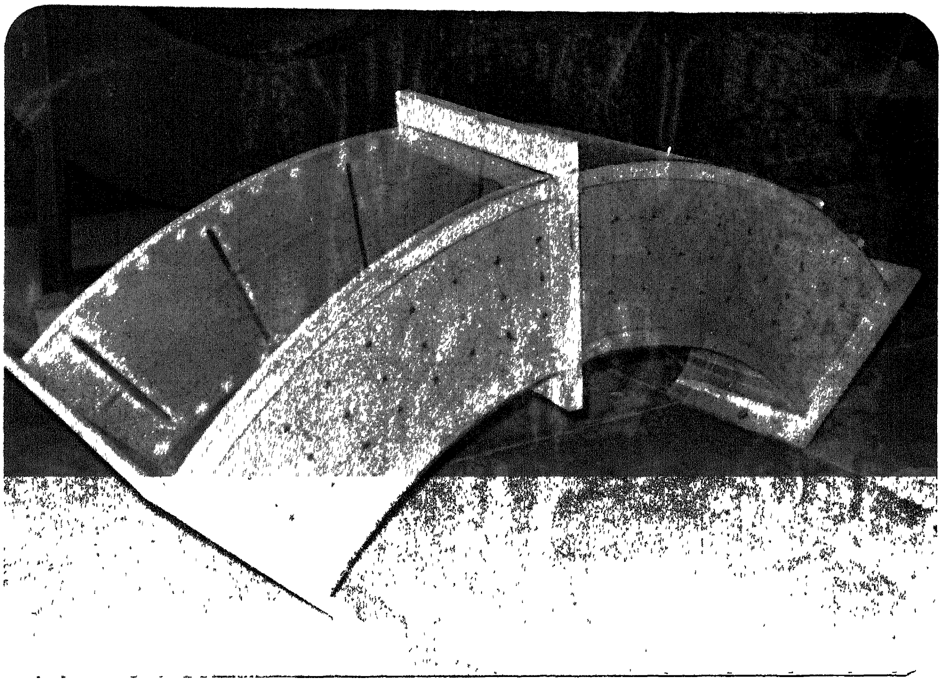
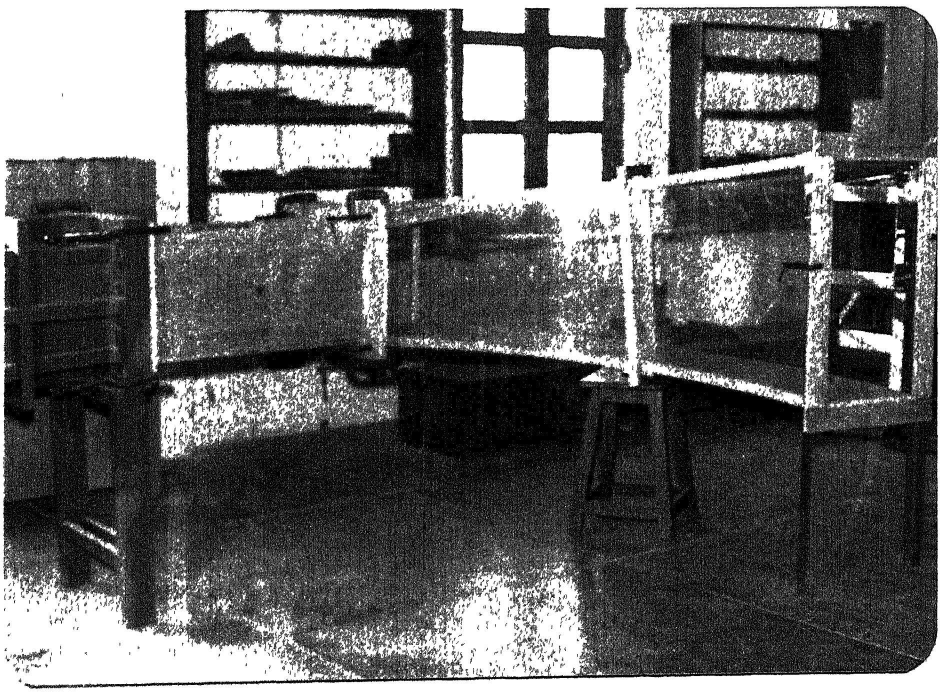








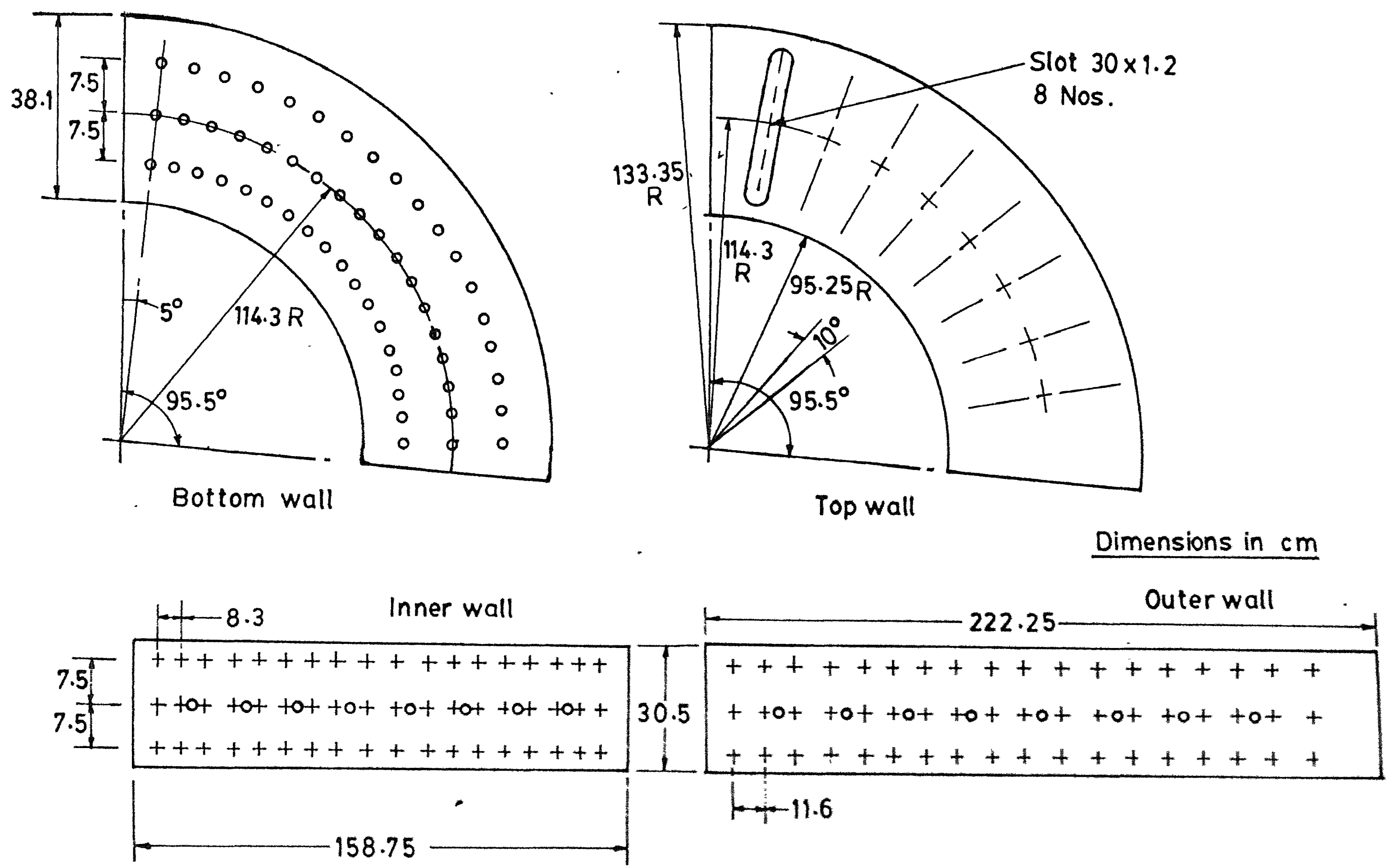


FIG. 1 CURVED DUCT GEOMETRY

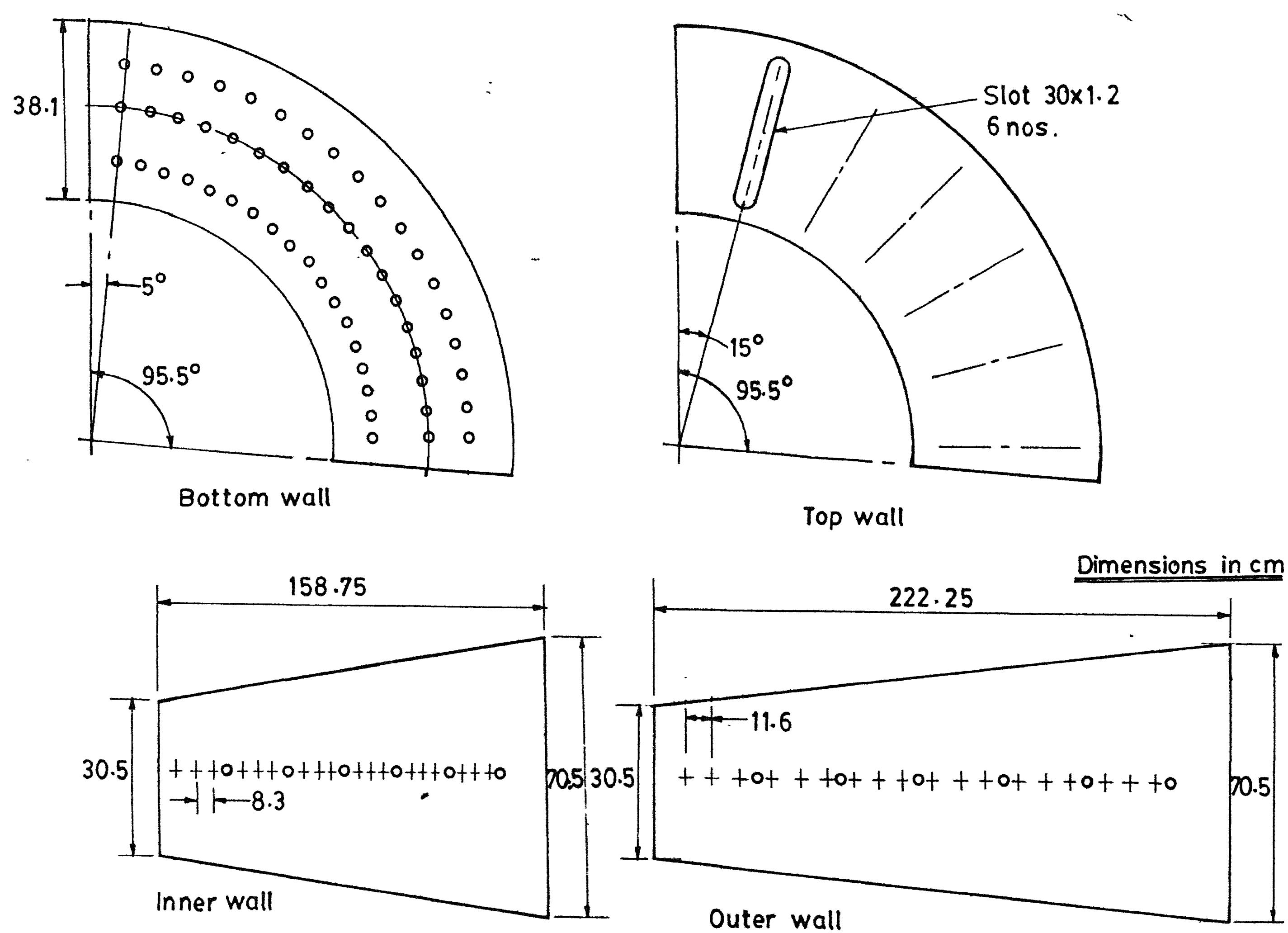
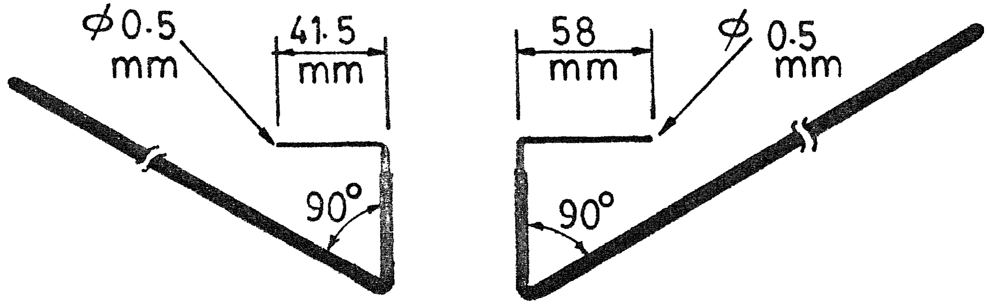
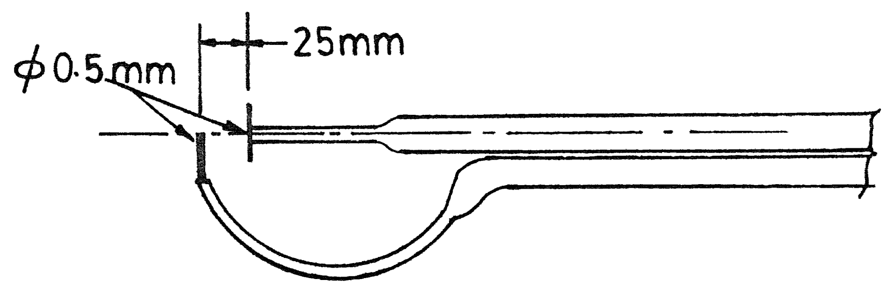


FIG. 2 CURVED DIFFUSER GEOMETRY



PITOT TUBE FOR INNER & OUTER WALL



PITOT- DISC PROBE

FIG.3 VARIOUS TYPES OF PROBES

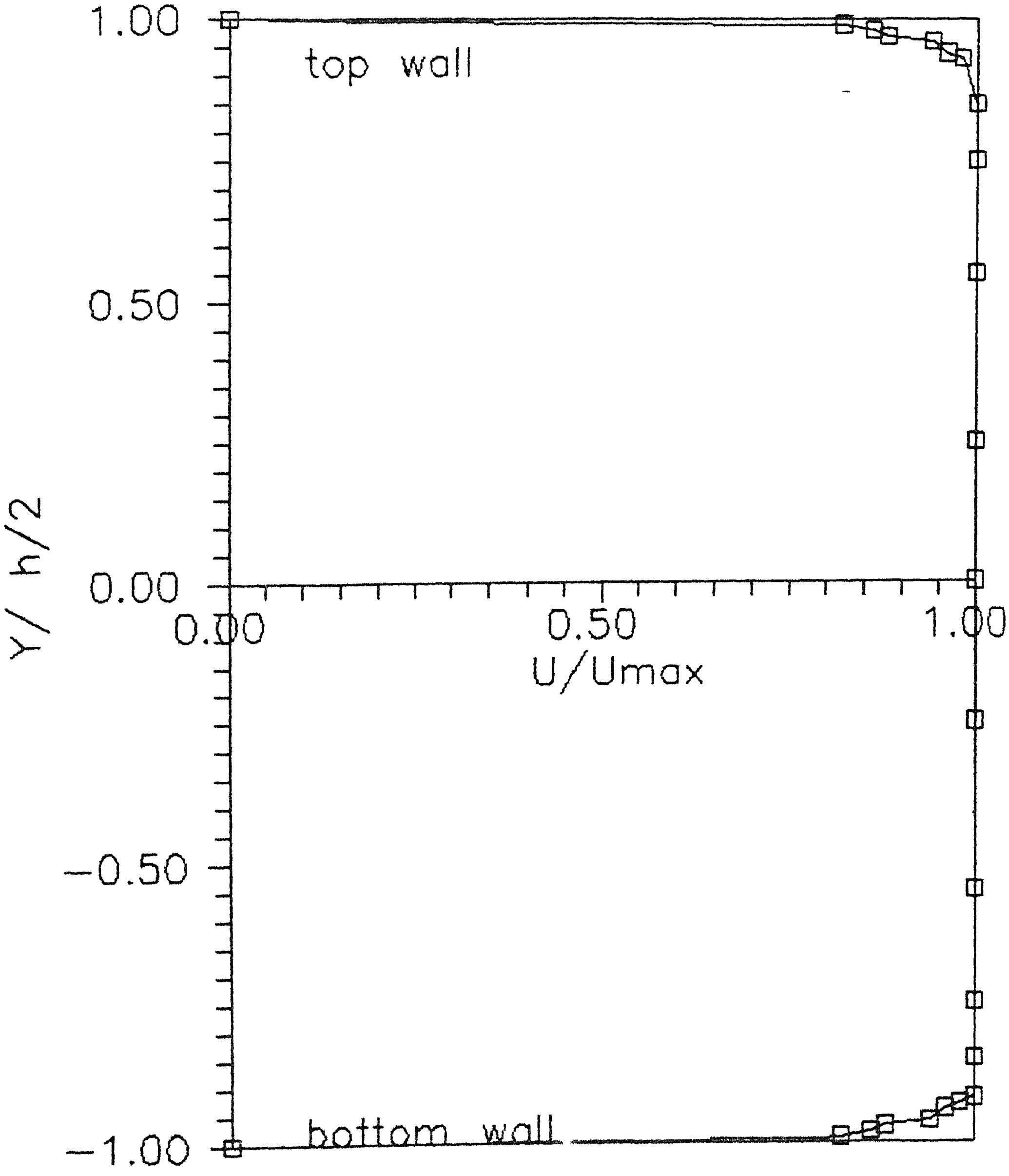


FIG 4 VELOCITY profile at the inlet.

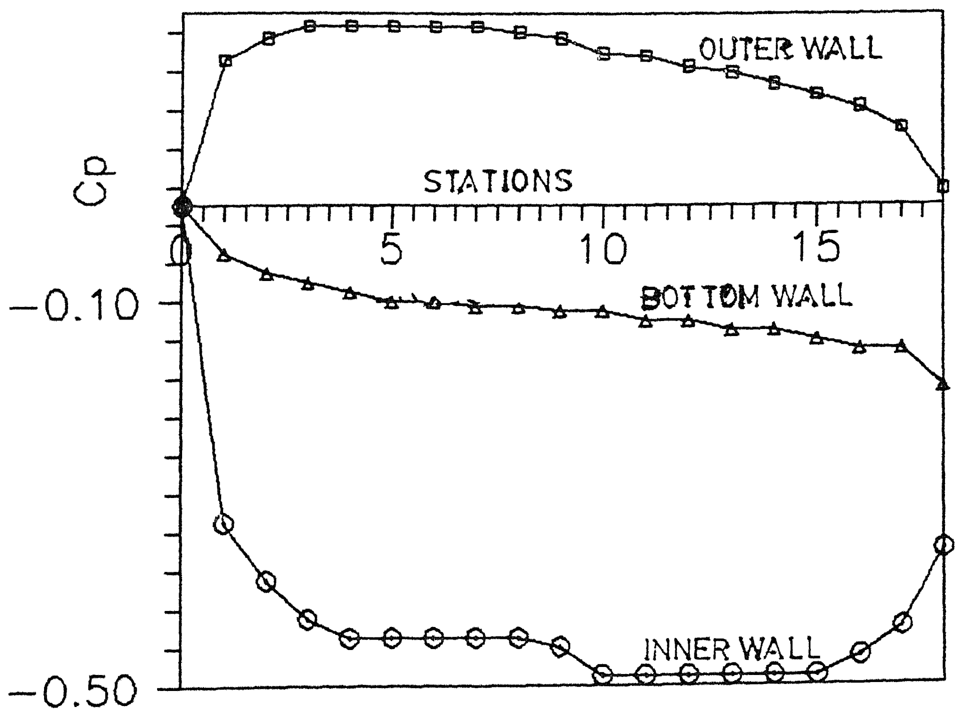


fig 5 pressure distributions along inner,outer and bottom walls of a curved duct.

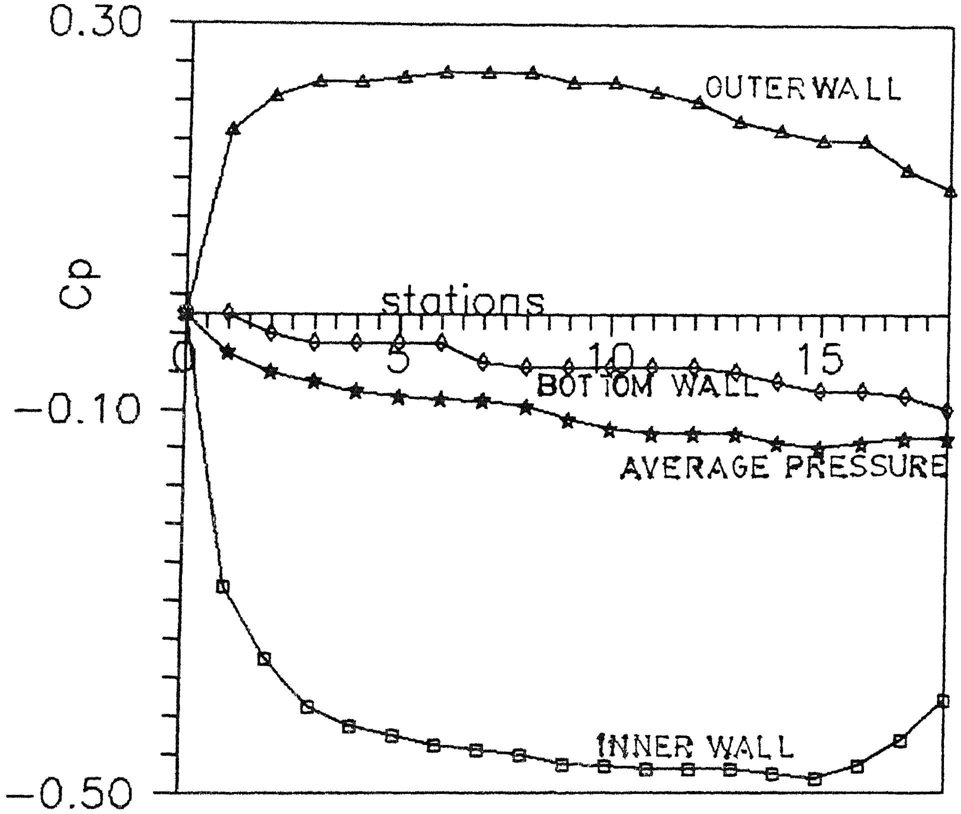


fig 6 pressure distributions along inner,outer and bottom walls of a curved duct with a parrel duct placed at its exit.

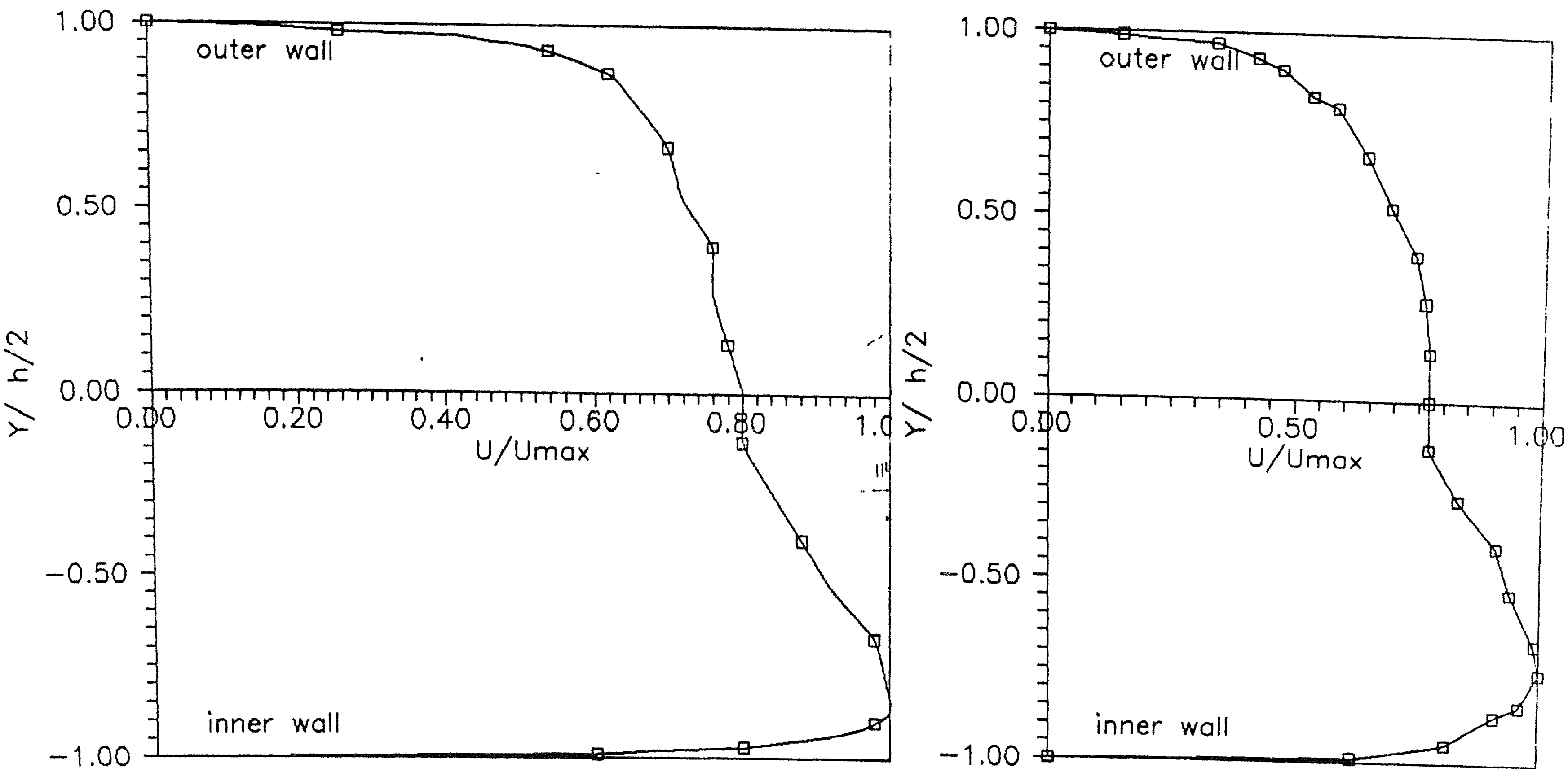


Fig 7 Velocity profiles at first and second stations of the curved duct.

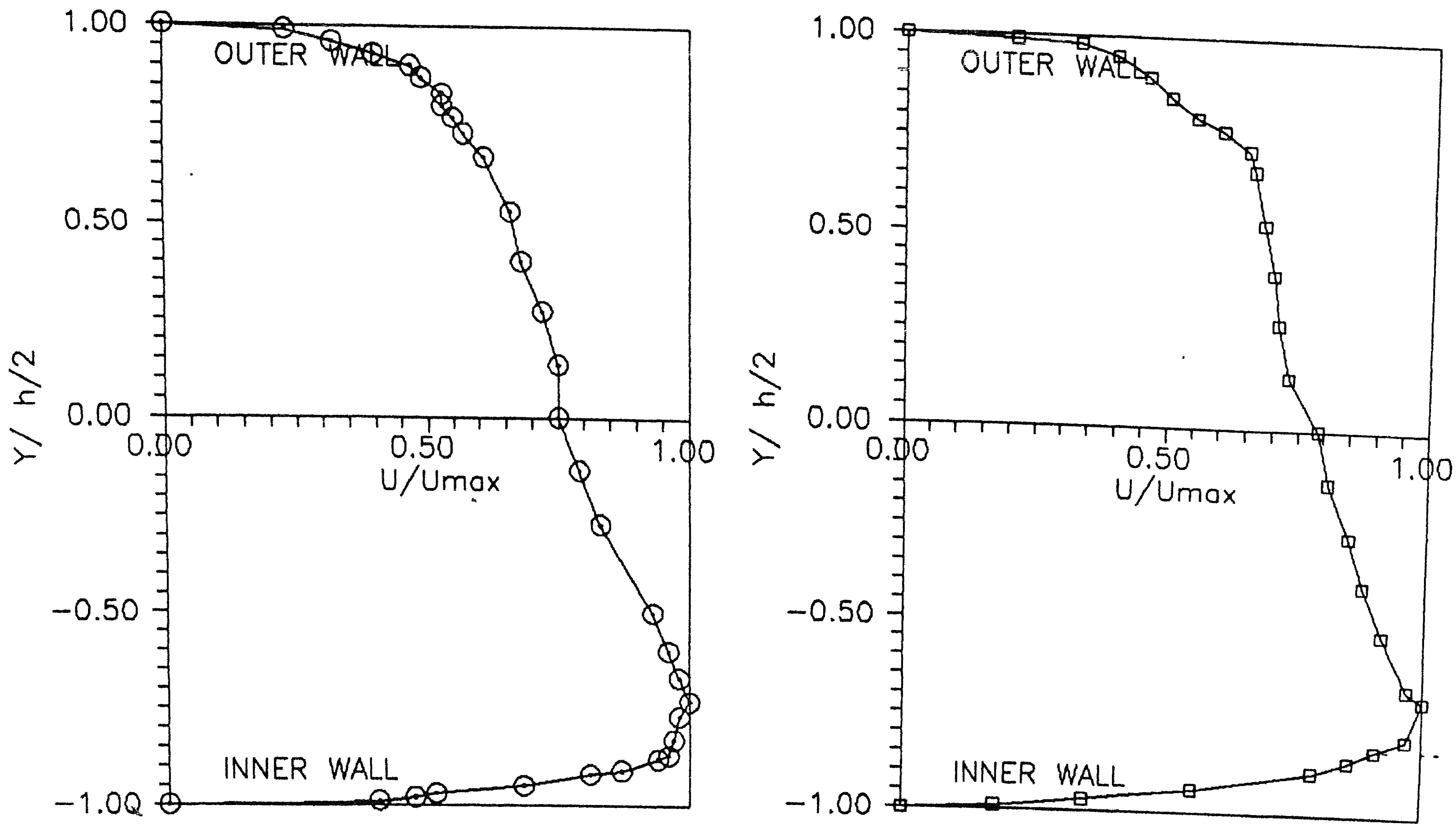
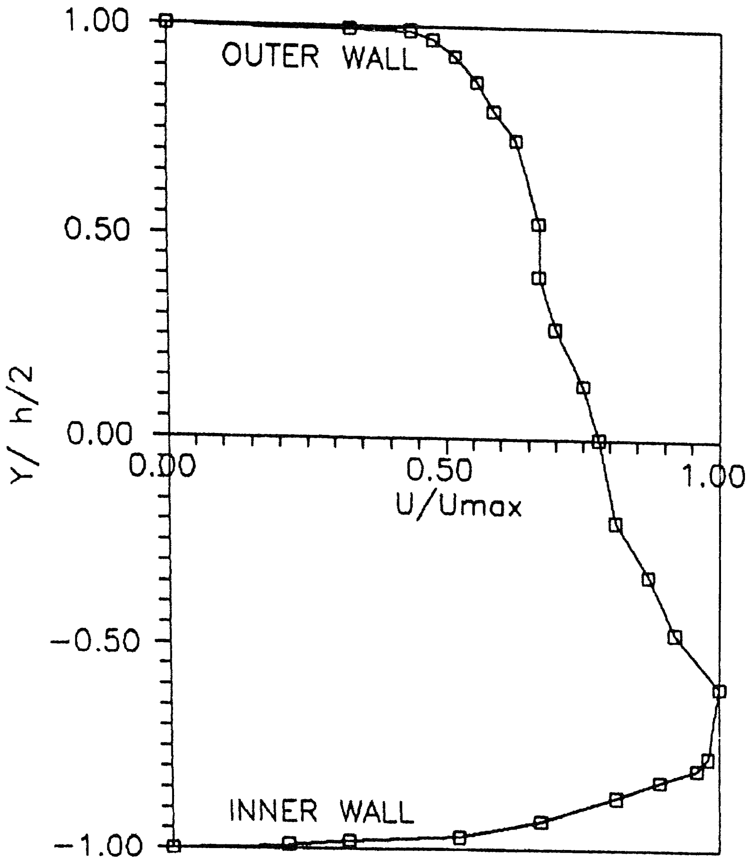


Fig 8 Velocity profiles at third and fourth stations of the curved duct.



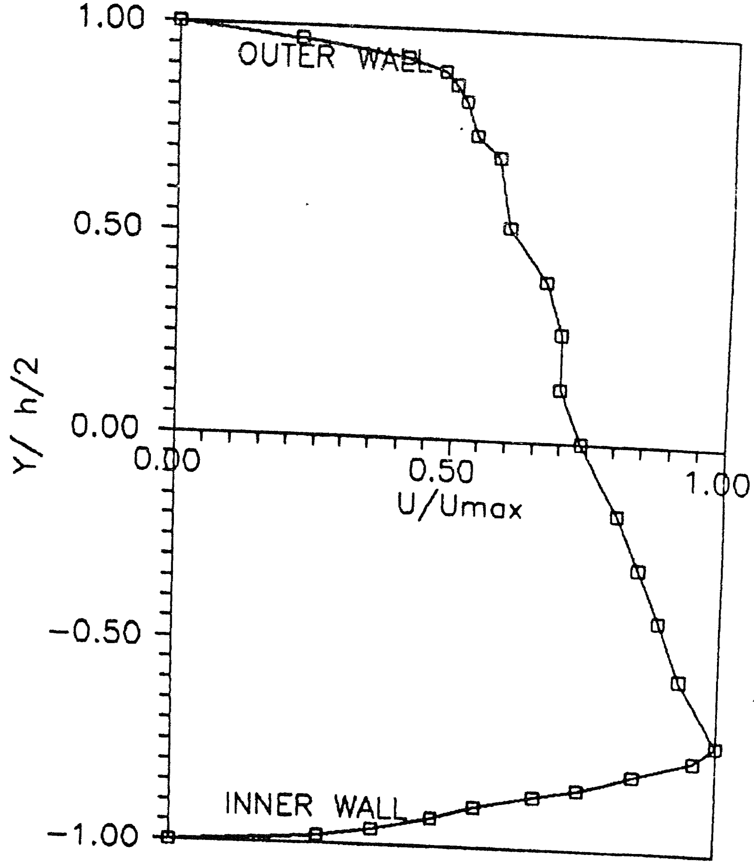


Fig 9 velocity profiles at fifth and sixth stations of the curved duct.

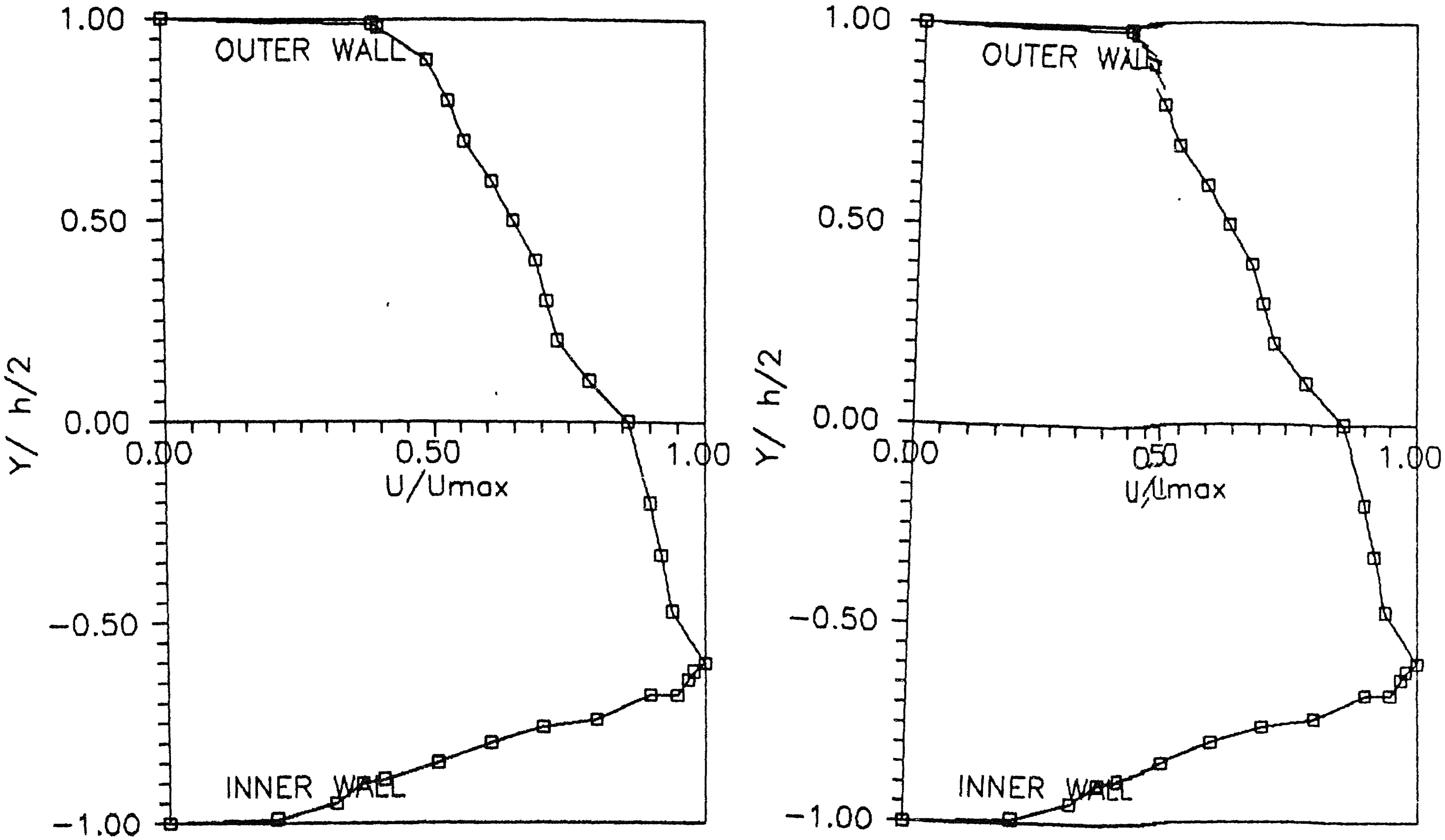


Fig 10 Velocity profiles at seventh and eightth stations of the curved duct.

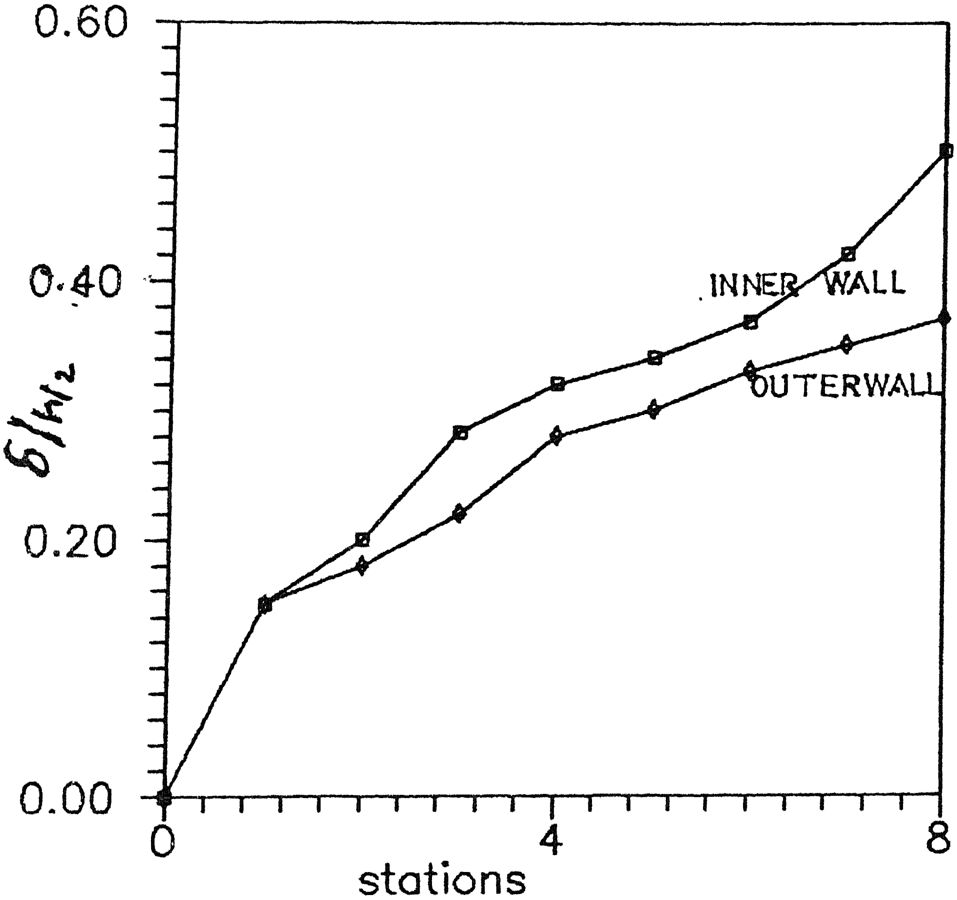


fig11 Boundary layer Thickness variation

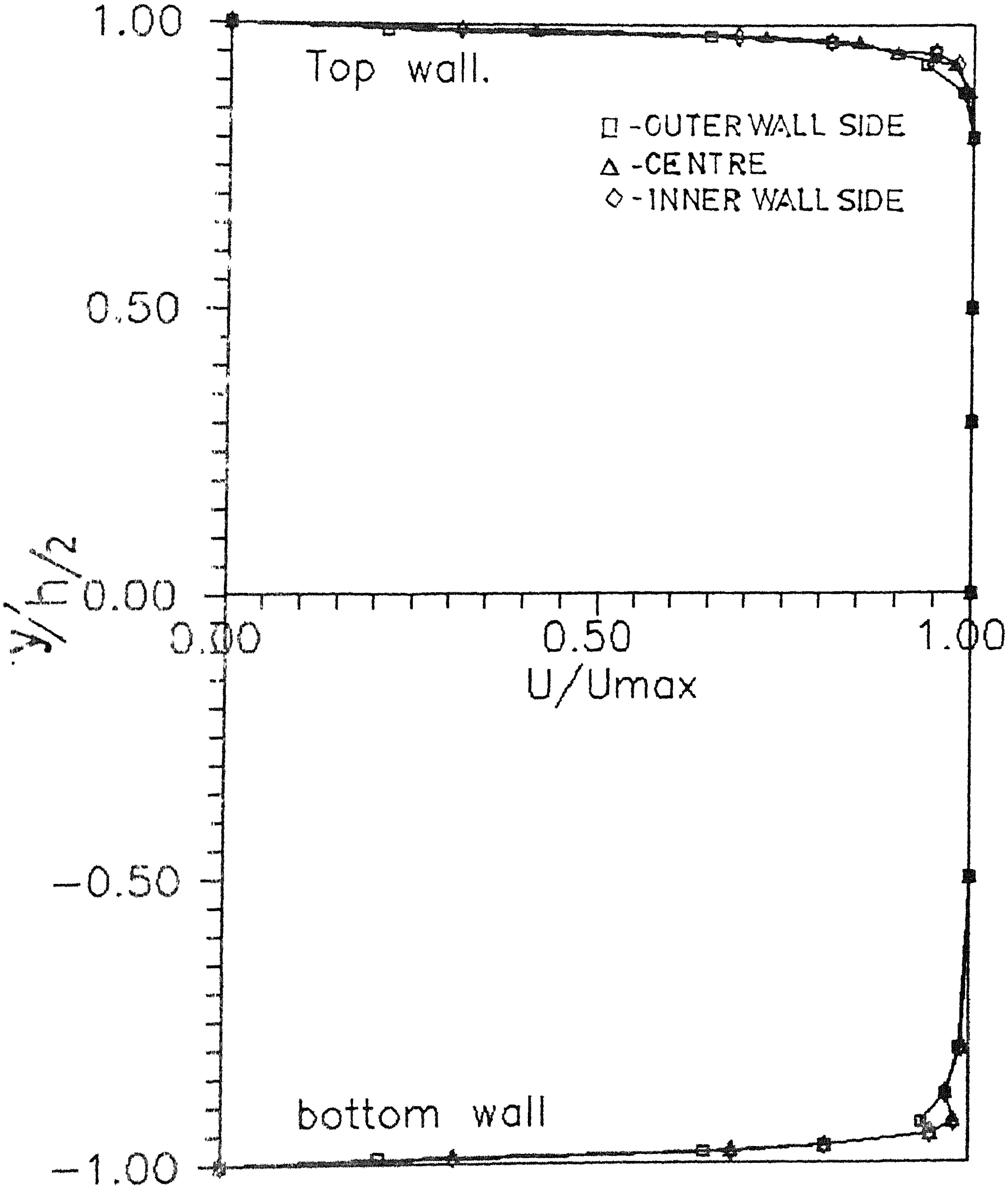


Fig 12 Velocity profile at the first station of a curved duct in the vertical direction.

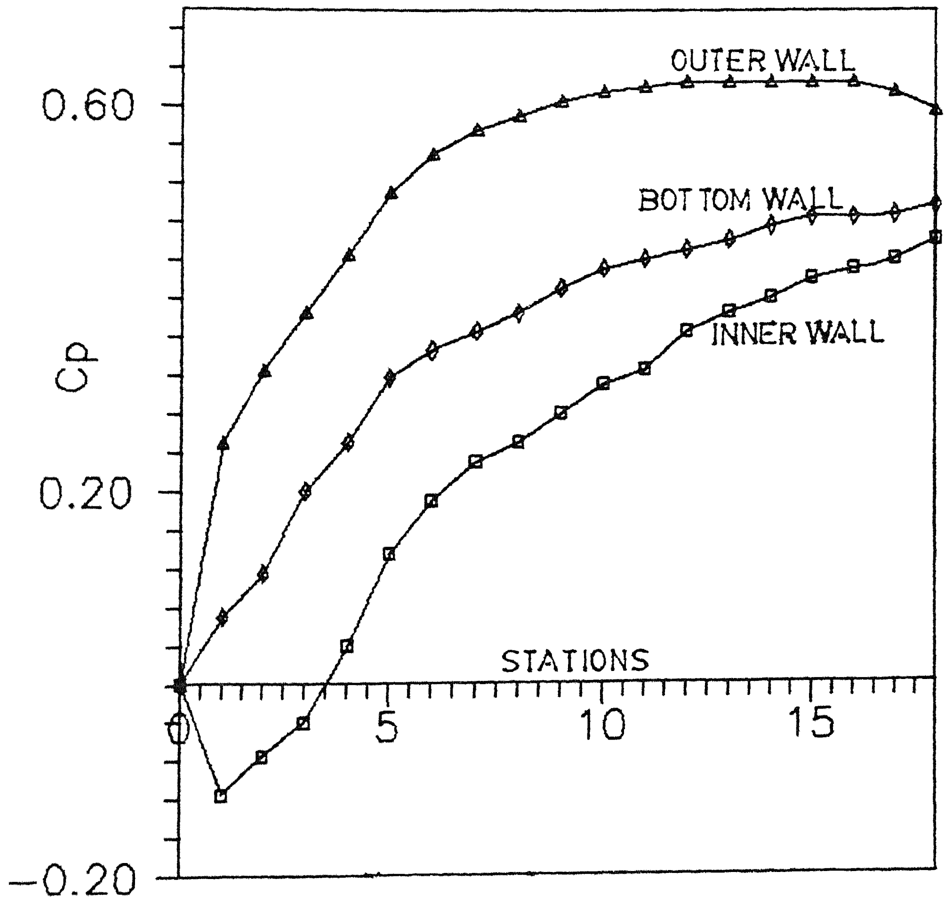


fig13 pressure distributions along inner,outer and bottom walls of a curved diffuser.

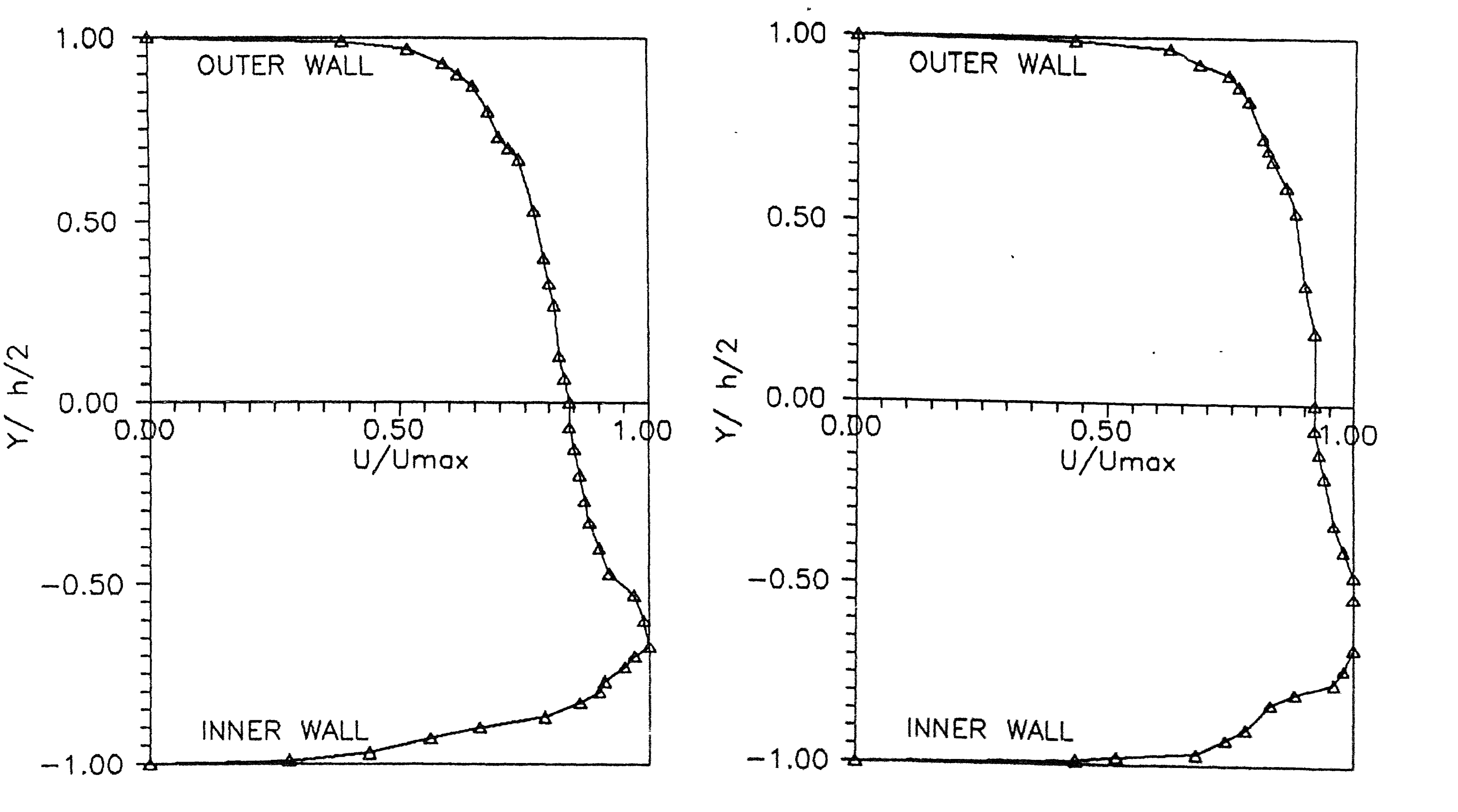


Fig 14 Velocity profiles at first and second stations of the curved diffuser.

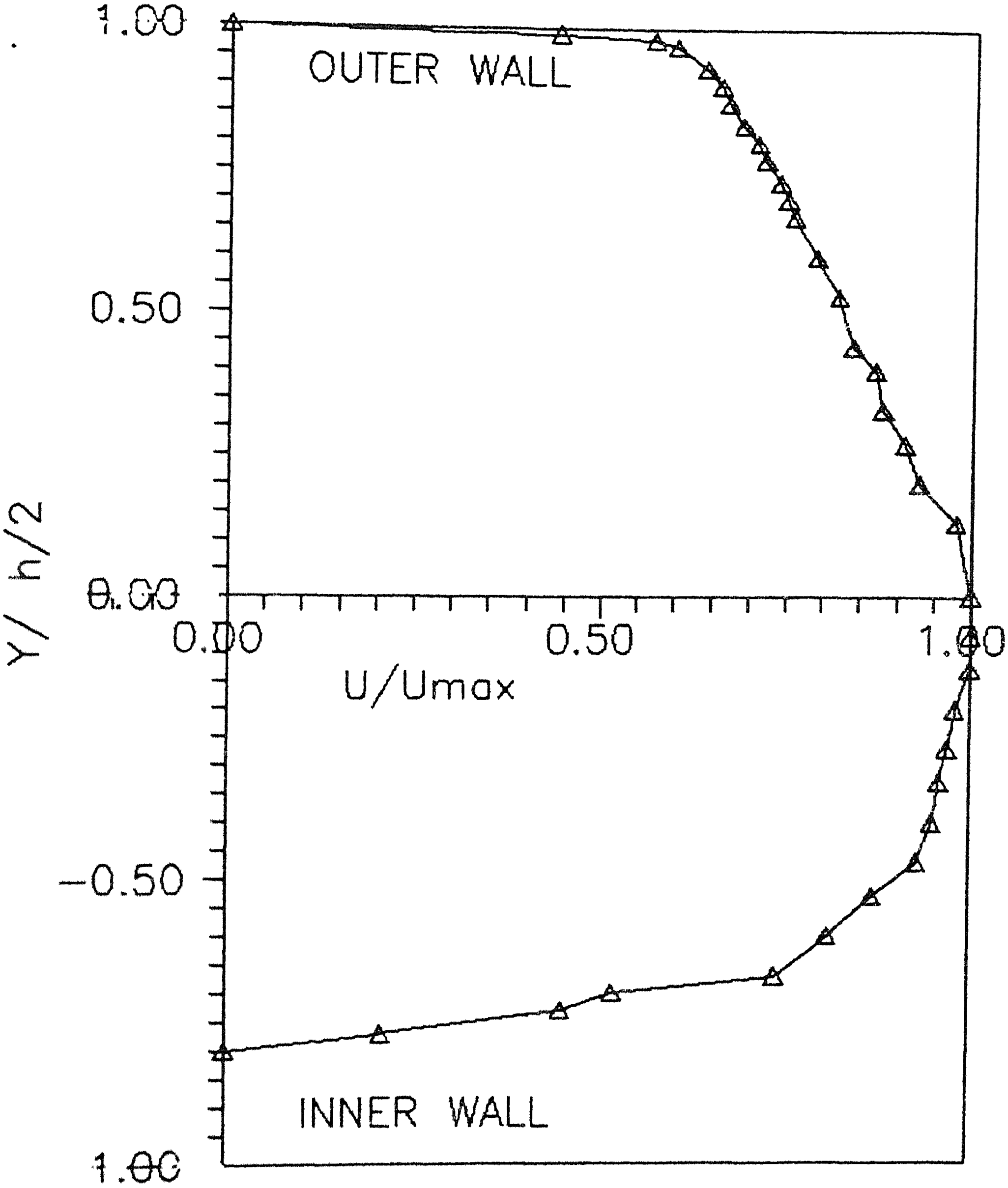


Fig 15 Velocity profile at the third station of the curved diffuser.

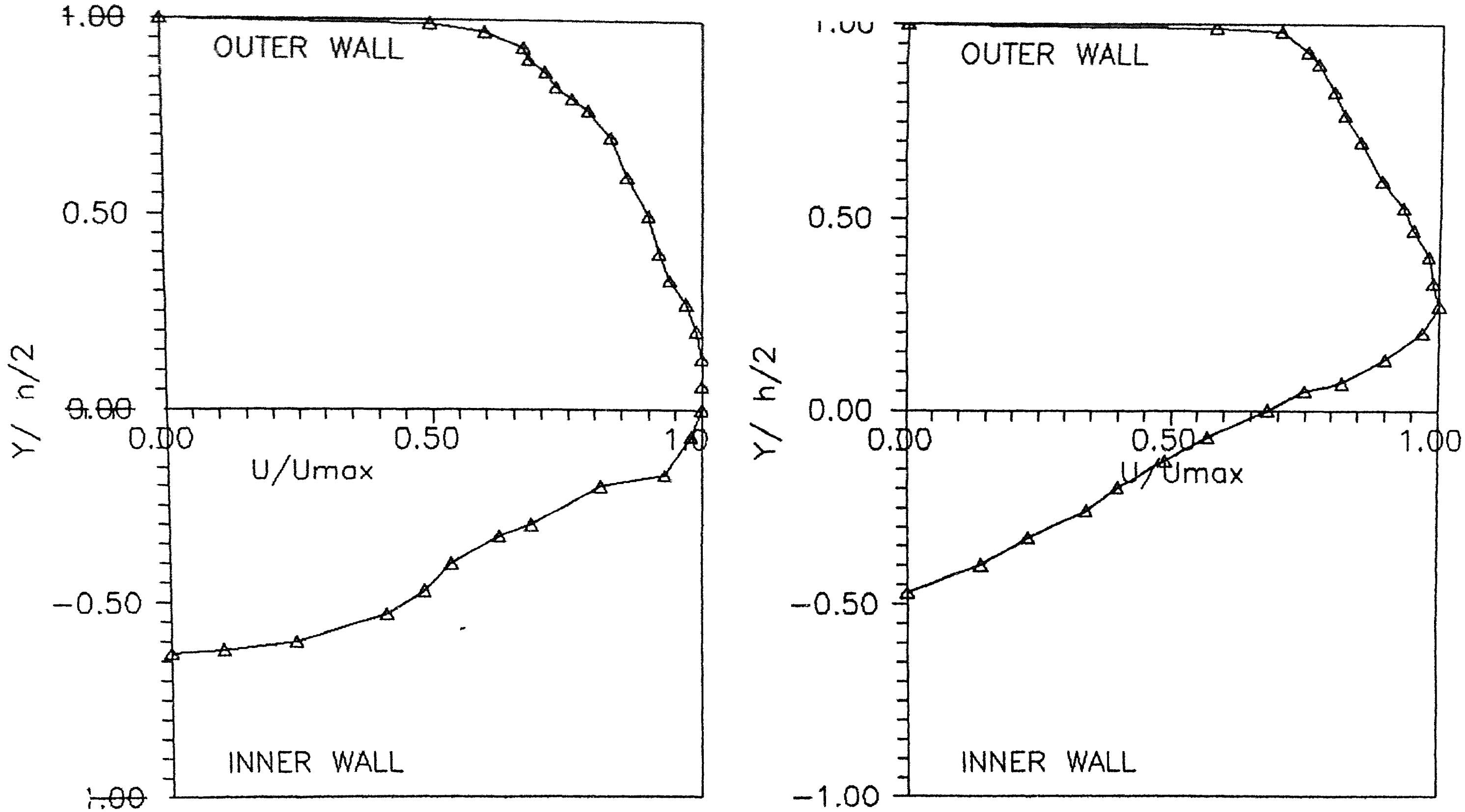


Fig 16 Velocity profiles at the fourth and fifth stations of the curved diffuser.

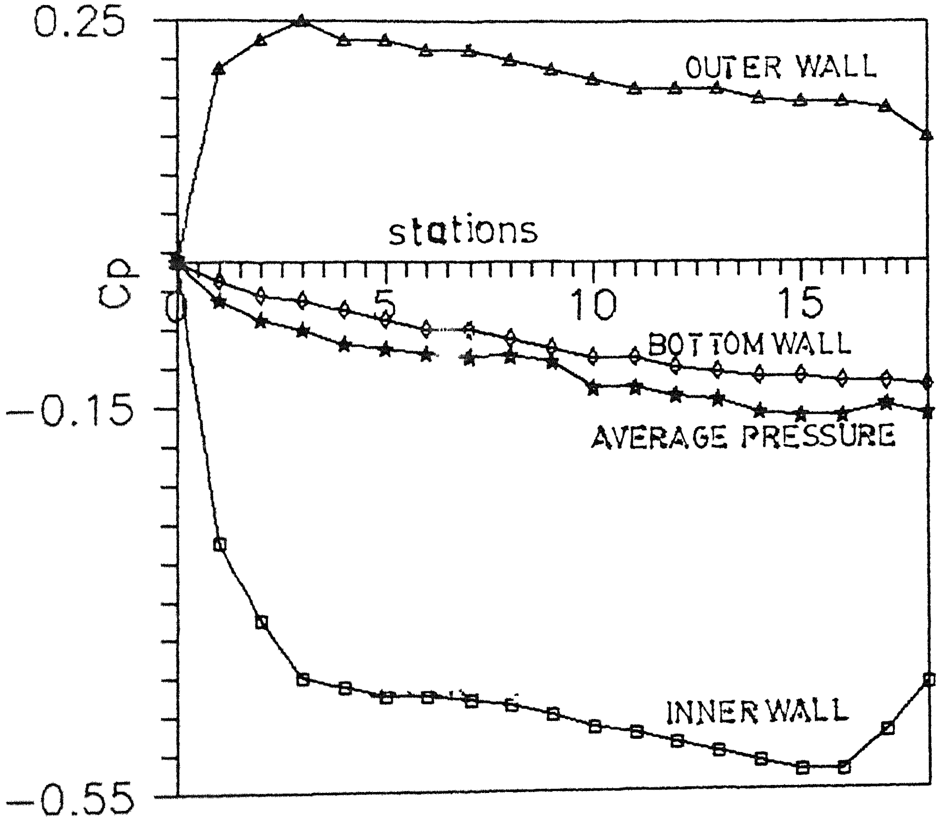


fig17 pressure distributions along inner,outer and bottomwalls of the curved duct with a grid placed at its exit.

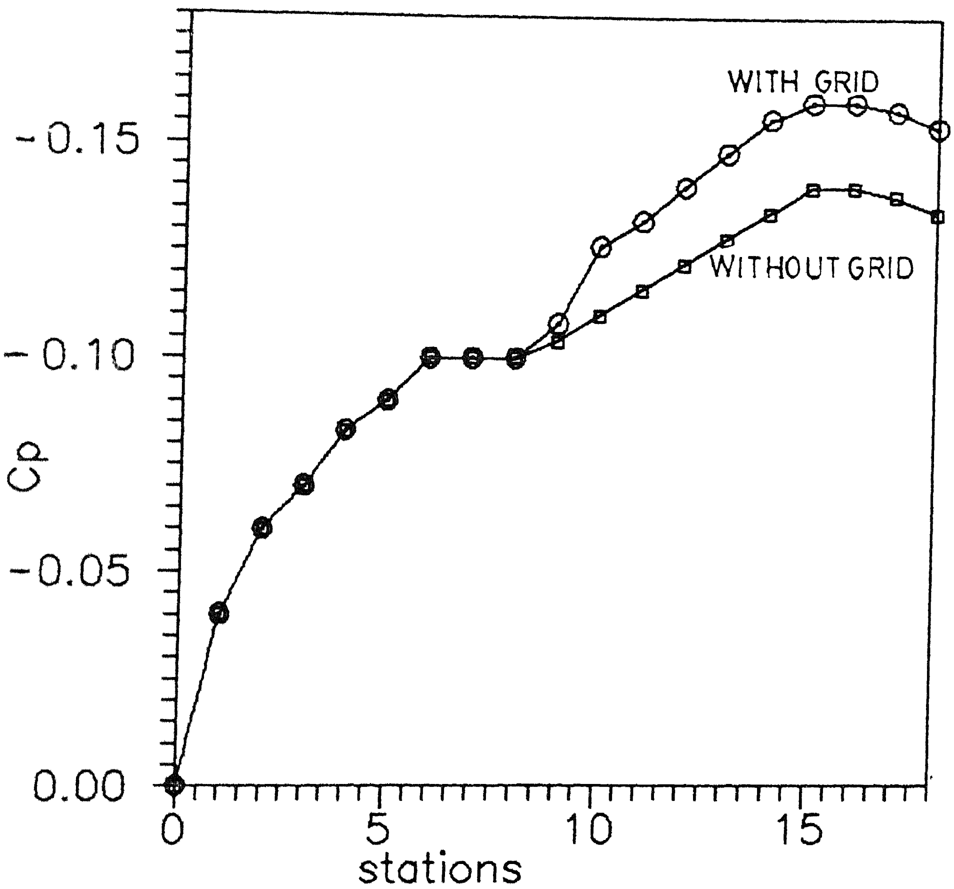


fig 18 Average pressure distributions in a curved duct with and without grid.

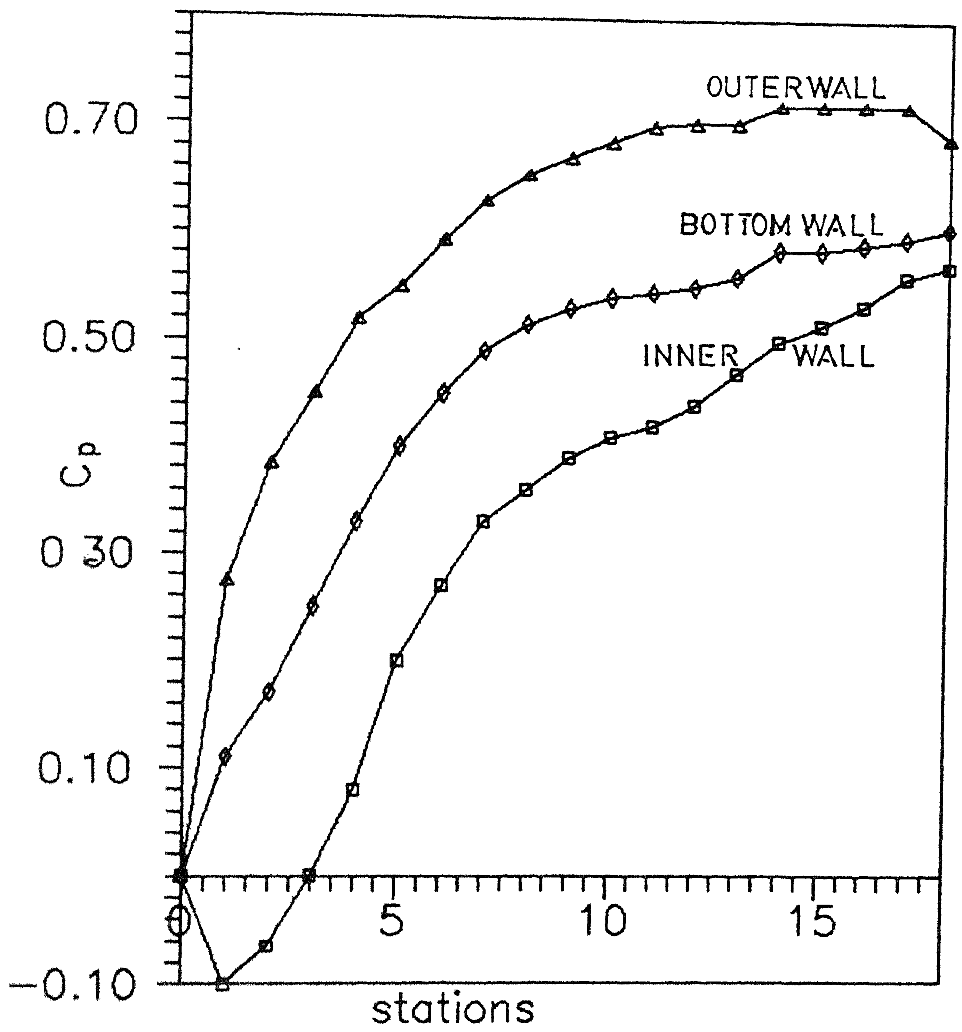


fig19 pressure distributions in a curved diffuser, with a tubulence grid,

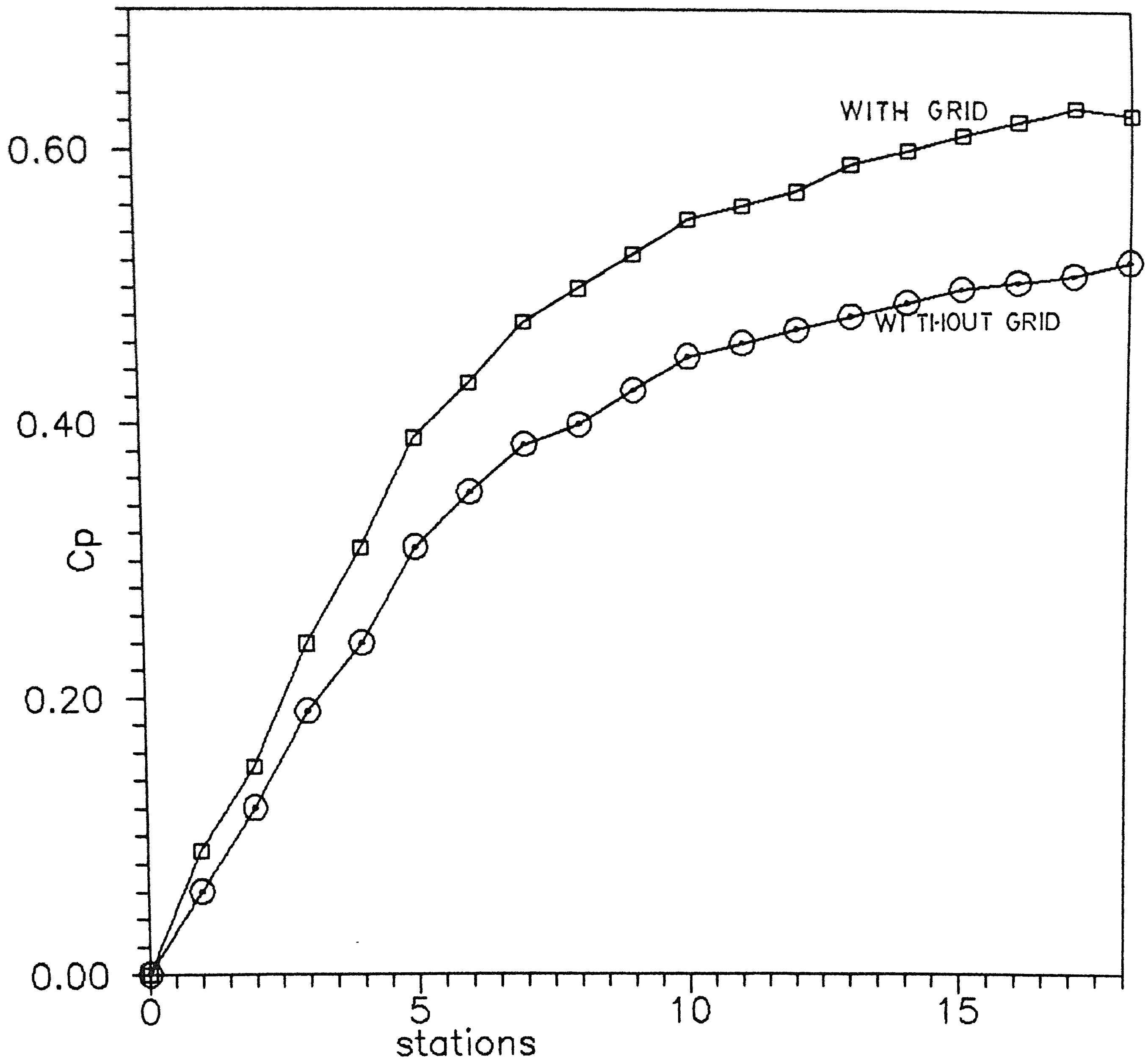


fig 20. average pressure distribution with and without grid in a curved diffuser

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